

**OPTIMIZED LOCATION DEPENDENT DATA
RETRIEVAL APPROACH FOR INTERNET OF
THINGS BASED ON NAMED DATA
NETWORKING**

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UNIVERSITI SAINS MALAYSIA

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by

ABOODI AHED HUSSEIN ALI

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LIST OF ABBREVIATIONS

6LowPAN	IPv6 over Low-power Wireless Personal Area Networks.
ALC	Adequacy Level Calculation
ANE	Announcement Entity
ATE	Attachment Entity
BGP	Border Gateway Protocol
CCA	Clear Channel Assessment
CCN	Content Centric Networking
CCNx	Content-Centric Networking Protocol (CCN Reference Implementation)
CDIL	Components for Device Identification and Location
CEE	Caching Everything Everywhere
CS	NDN's Content Store
CSA	Communication Signaling Algorithm
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
dBm	Decibel Milliwatts
DBus	Message Bus System
DNS	Domain Name Service
DR	Data-Retrieval
DRA	Data-Retrieval Attempts
DRF	Data-Retrieval Traffic
DRL	Data-Retrieval Latency
DRO	Data-Retrieval Overhead
DRPH	Data-Retrieval Producer Hit
DRR	Data-Retrieval Requests
DRT	Data-Retrieval Bytes or Throughput

ENE	Enhanced NDN Entities (or Proposed Solution)
ES	Experiment Step
ESs	Experiment Steps
F2A	Face-to-Area Table
FCA	Freshness Control Algorithm
FIB	NDN's Forwarding Information Base
FIFO	First In First Out
FTI	Full-Time Interest or Continuous Interest
GDR	Group Data-Retrieval
GDRL	Group Data-Retrieval Latency
GHz	Gigahertz
GID	Group Interest Delivery
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GRD-C	Group Reply Delivery to Consumer
HMAC	hash-based message authentication code
ICN	Information Centric Networking
ICWSAN	ICN approach for Wireless Sensor and Actor Network
ID	Interest Delivery
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IM	Island Manager
IoT	Internet of Things
IP	Internet Protocol
IPC	Inter-Process Communication
IPv6	Internet Protocol version 6
ITS	Intelligent Transportation System

IVC	Intravehicular Communication
JSON	JavaScript Object Notation
KDS	Key Distribution Services
LAFS	Learning-based Adaptive Forwarding Strategy for NDN-based IoT
LAL	Link Adaptation Layer
LCD	Leave Copy Down
LCE	Leave Copy Everywhere
LDTMIN	Low Defer Time Multiple Intermediate Node
LFF	Least Fresh First
LFU	Least Frequently Used
LNA	Low Noise Amplifier
LPM	Longest Prefix Match
LRU	Least Recently Used
MAC	Media Access Control
MDP	Markov Decision Process
MEMS	micro-electromechanical systems
MF	Multicast Forwarding
MGRS	Military Grid Reference System
NDN	Named Data Networking
NDN-RIOT	NDN Protocol Stack for RIOT-OS
NDP	Neighbor Discovery Protocol
NFD	NDN Forwarding Daemon
NHT	Next Hop Table
NIC	Network Interface Card
NML	Network Message Loss
NS-2	Network Simulator Version 2
NSB	Named Service Bus

NSF	United State National Science Foundation
NT	Network Traffic
NTO	Network Traffic Overhead
oRiA	out-Range-In-Area
OS	Operating System
OSPF	Open Shortest Path First
PA	Power Amplifier
PARC	Palo Alto Research Center; formerly Xerox PARC)
PDC	Path-Distance Calculation
PIT	NDN's Pending Interest Table
RD	Reply Delivery
RF	Radio Frequency
RFID	Radio-Frequency Identification
RIOT-OS	RIOT OS, A Real-time Operating System for IoT
RPi	Raspberry Pi
RR	Routing Reference
RRE	Routing References Extension
RSSI	Received Signal Strength Indicator
RTT	Round-Trip-Time
RX	Receive
SDB	Service Discovery Broker
SLA	Service Level Agreement
SME	Semantic Matching Engine
SNR	Signal-to-Noise Ratio
SNUI	Status of the Next Upstream Interface
SOA	Service-Oriented Architecture
SoC	System on Chip

SPD	Shortest Path-Distance
TCP	Transmission Control Protocol
TI	Texas Instruments
TLV	Type-Length-Value Encoding
TX	Transmit
UCLA	University of California, Los Angeles
UDP	User Datagram Protocol
USB	Universal Serial Bus
USM	Universiti Sains Malaysia
VIN	Vehicular Information Network
WSAN	Wireless Sensor and Actor Networks
WSN	Wireless Sensor Network
WSNs	Wireless Sensor Networks

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**PENDEKATAN PEMEROLEHAN DATA BERDASARKAN LOKASI YANG
DIPERTINGKATKAN UNTUK INTERNET BENDA BERASASKAN
RANGKAIAN DATA TERNAMA**

ABSTRAK

Internet benda (IoT) memerlukan mekanisme pengambilan data yang cepat, mudah disesuaikan, dan boleh diskalakan untuk memenuhi keperluan data berorientasikan kandungan dan senario berorientasikan lokasi. Rangkaian Data Ternama (NDN) menawarkan alternatif yang menjanjikan kepada seni bina berasaskan IP tradisional dengan memberi tumpuan kepada kandungan daripada komunikasi berasaskan hos. Walau bagaimanapun, penyelesaian NDN sedia ada menghadapi cabaran dalam persekitaran yang terhad sumber, termasuk sokongan terhad untuk penghantaran dan pengambilan data berorientasikan lokasi, ketidakcekapan dalam penghantaran multikas, dan lebihan penghantaran yang tinggi. Penyelidikan ini memperkenalkan E-NDN, iaitu seni bina NDN yang ditambah baik dan disesuaikan untuk persekitaran IoT tanpa wayar yang terhad sumber. E-NDN mengintegrasikan tiga modul teras: (1) Skema Penamaan DLH dan Penghantaran Berorientasikan Tempatan, yang menggabungkan penamaan hierarki berasaskan lokasi dengan prosedur penindasan Interest yang peka jarak dan penghantaran sandaran untuk meningkatkan kebolehpercayaan; (2) Penamaan dan Penghantaran Berasaskan Wildcard, yang mengoptimumkan pengambilan data multikas dengan menyatukan permintaan Interest, mengurangkan redundansi, dan membolehkan penyasaran lokasi yang lebih dekat; dan (3) Modul Pemilihan Laluan, yang secara dinamik mengoptimumkan perutean berdasarkan jarak dan keupayaan nod, sambil mentakrifkan dan membolehkan had domain siaran untuk mengurangkan kesesakan. Ketiga-tiga modul ini membentuk Skema Penamaan Hibrid dan Strategi

Pengantaran Dua Mekanik, yang membolehkan integrasi lancar antara pengambilan data berorientasikan kandungan dan berorientasikan lokasi. Seni bina ini disahkan melalui eksperimen dunia sebenar menggunakan testbed di bangunan USM dan dibandingkan dengan LAFS serta NDN-RIOT. Keputusan menunjukkan peningkatan ketara dalam beban pengambilan (pengurangan sebanyak 14.4%-32.3%), kebolehpercayaan pengantaran berorientasikan lokasi (sehingga 6.9% lebih tinggi), dan kependaman multikas berorientasikan lokasi (sehingga 15% lebih rendah). Penemuan ini menetapkan E-NDN sebagai seni bina yang kukuh dan adaptif untuk sistem IoT masa depan, yang menangani cabaran utama dalam kecekapan sumber, kebolehpercayaan, dan kebolehadaptasian.

OPTIMIZED LOCATION DEPENDENT DATA RETRIEVAL APPROACH FOR INTERNET OF THINGS BASED ON NAMED DATA NETWORKING

ABSTRACT

The Internet of Things (IoT) demands efficient, adaptable, and scalable data retrieval mechanisms to meet the dual requirements of data-oriented and location-dependent host-oriented scenarios. Named Data Networking (NDN) offers a promising alternative to traditional IP-based architectures by focusing on content rather than host-based communication. However, existing NDN-based solutions face challenges in resource-constrained environments, including limited support for location-dependent data delivery and retrieval, inefficiencies in multicast forwarding, and high transmission overhead. This research introduces E-NDN, an enhanced NDN architecture tailored for wireless resource-constrained IoT environments. E-NDN integrates three core modules: (1) the DLH Naming Scheme and Local-First Forwarding, which combines hierarchical location-enabled naming with proximity-aware Interest suppression and backup forwarding procedures for enhanced reliability; (2) Wildcard-Based Naming and Forwarding, which optimizes multicast data retrieval by consolidating Interest requests, reducing redundancy, and enabling more proximate location targeting; and (3) the Path-Selection Module, which dynamically optimizes routing based on node proximity and capabilities, while defining and enabling broadcast domain limits to mitigate congestion. These modules form a Hybrid Naming Scheme and Dual-Mechanic Forwarding Strategy, enabling seamless integration of data-oriented and location-dependent data retrieval. The architecture is validated through real-world experiments using a testbed in the USM building and compared with LAFS and NDN-RIOT. Results show significant improvements in retrieval overhead (14.4%-32.3% reduction), location delivery

reliability (up to 6.9% higher), and location-dependent multicast latency (up to 15% lower). These findings establish E-NDN as a robust and adaptive architecture for future IoT systems, addressing key resource efficiency, reliability, and adaptability challenges.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The Internet of Things (IoT) interconnects a vast array of physical devices and digital systems, creating an ecosystem that demands efficient, scalable, and adaptable communication frameworks. However, the constrained nature of IoT environments—with limitations in energy, processing, memory, and bandwidth—poses significant challenges to traditional networking approaches. These environments require robust data retrieval mechanisms that cater to both data-oriented and location-dependent host-oriented scenarios, where information retrieval needs are shaped by content and physical proximity alike.

To address these challenges, the current networking architecture relies on IP-based models and protocols, such as 6LoWPAN and MQTT, which extend the traditional TCP/IP stack to support constrained IoT environments. However, the host-centric nature of the IP model imposes inherent limitations, particularly in scenarios involving frequent topology changes or location-dependent data retrieval. The reliance on physical addresses and centralized control results in communication overhead, inefficiencies, and scalability issues. Moreover, IP-based solutions often struggle to meet the stringent requirements of IoT applications, such as low latency, minimal energy consumption, and seamless mobility (Al-Ward et al., 2022; Azamuddin et al., 2023; Quevedo & Corujo, 2022).

To overcome these limitations, the Named Data Networking (NDN) (Zhang et al., 2014), paradigm has emerged as a transformative solution. As part of the broader Information-Centric Networking (ICN) architecture (Safwat et al., 2022),

NDN shifts the focus from host-based to content-based communication. Unlike IP-based systems, NDN retrieves content using unique data names rather than physical addresses, decoupling content from its host location. This approach introduces inherent advantages, including in-network caching, simplified management, scalability, and enhanced security. These features make NDN a compelling choice for IoT applications (Djama et al., 2020).

Despite its potential, applying NDN in resource-constrained IoT environments presents unique challenges. NDN's multicast nature and data-centric design can introduce transmission overhead or data loss, particularly in scenarios requiring device-specific or location-sensitive data retrieval. Additionally, NDN lacks built-in mechanisms for location-based forwarding and device identification, which are critical in IoT applications like indoor navigation and asset tracking. Addressing these limitations requires incorporating location attributes into NDN's architecture while preserving its core features, such as caching, scalability, and data-centric security.

This thesis explores the application of NDN in enabling efficient location-dependent data retrieval for IoT environments, particularly Wireless Sensor Networks (WSNs) with constrained resources. The study investigates innovative approaches to integrate location attributes into NDN, aiming to optimize data delivery and retrieval, reduce transmission overhead, and enhance network efficiency. This chapter outlines the foundation for this research. Section 1.2 provides the background, discussing IoT, WSN technologies, the transition from TCP/IP to NDN, and the challenges of location-dependent data retrieval. The problem statement is elaborated on in Section 1.3, with research objectives, scope, contributions detailed, and methodology in subsequent sections.

1.2 Background

This section discusses the background of three major aspects of the thesis. First, it outlines the evolution of the Internet of Things. Second, it describes the trajectory of wireless sensor networks and their technology. Third, it presents the emerging architecture of the information-centric systems network.

1.2.1 Internet of Things

The Internet of things has evolved from the convergence of wireless technologies, micro-electromechanical systems (MEMS), and the Internet, and is sometimes referred to as the Internet of Everything (Langley et al., 2021). The Internet began as a platform for computers, serving as a source of vast information and services. With the rise of social networks, it evolved into the “Internet of People,” extending connectivity to individuals.

The advancements in mobile data services, such as 5G and wireless communication technologies, have introduced the concept of “Ubiquitous Computing.” Devices like smartphones and tablets were designed not only for Internet connectivity but also for intelligent tasks, using embedded sensors, Global Positioning Systems (GPS), and actuators. These innovations enabled physical objects to connect to cyberspace, interacting with the real world through the Internet, leading to the term “Internet of Things.”

IoT devices range from small, resource-constrained sensors used for data collection and control to more advanced systems capable of real-time, context-aware data processing (Choudhary & Meena, 2022). Such devices facilitate tasks like location-dependent data retrieval, where real-time information is gathered and processed based on specific geographical contexts.

Nowadays, IoT connects billions of heterogeneous devices, or “Things,” to provide global services and access to information. This growth has been driven by the affordability of resource-constrained data acquisition devices, the widespread adoption of smartphones, and wireless communication standards such as IEEE 802.15.4.

1.2.2 Wireless Sensor Technology

WSNs serve as a crucial bridge between the physical and digital worlds in IoT. These networks are resource-constrained and designed for long-term, low-cost wireless connectivity to simple and inexpensive devices (Cena et al., 2020). WSNs are widely deployed in applications such as environmental monitoring, military operations, smart grids, traffic management, weather tracking, and forest fire detection.

WSNs rely on spontaneous network creation and wireless communication to facilitate short-distance interactions among nodes (Din et al., 2021). These networks transmit data from numerous sensors over wide areas without requiring a wired infrastructure. The nodes are typically static, compact, and battery-powered, with limited memory and computational capabilities. Energy efficiency is critical for these nodes due to their constrained power sources (Kandris et al., 2020).

Various communication technologies are employed in WSNs, including IEEE 802.15.4, Wi-Fi, Bluetooth, ZigBee, and 5G. IEEE 802.15.4 is especially prominent due to its low power consumption, making it ideal for battery-operated devices in low-rate wireless personal area networks (LR-WPANs) (Cena et al., 2020; Jaksic et al., 2023). Its software-based MAC mechanisms simplify the implementation of lower layers while allowing flexibility for higher-layer protocols (Ghori et al., 2020).

However, energy efficiency can be compromised by inaccurate performance estimation, leading to energy loss from retransmissions in automatic repetition schemes or increased processing in forward error correction schemes. On top of that, factors such as fading, interference, and noise can adversely impact other crucial network parameters, including latency and throughput (Jaksic et al., 2023). This can be exemplified in congested network scenarios, where resource-constrained devices have inconsistent or lack a collision avoidance scheme. The shared wireless transmission channel in the physical layer leads to increased collisions, degrading network performance as congestion grows.

1.2.2(a) From TCP/IP to NDN

The traditional TCP/IP stack has been the cornerstone of IoT connectivity, facilitating the integration of resource-constrained devices into digital networks. However, this model often struggles to meet the fundamental requirements of IoT environments. To address these challenges, the IETF introduced protocols like 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks), which allows IPv6 networking over IEEE 802.15.4, and RPL (Routing Protocol for Low-power and Lossy networks), which supports multi-hop topologies (Ashrif et al., 2024). These solutions include mechanisms such as header compression and packet fragmentation, which can add overhead, processing demands, and memory usage in already constrained IoT devices, potentially increasing collisions (Abane et al., 2020).

At the application layer, lightweight protocols like CoAP (Constrained Application Protocol) and MQTT (Message Queuing Telemetry Transport) provide alternatives to HTTP. CoAP operates over UDP or DTLS for session security, while MQTT facilitates many-to-many messaging via a publish/subscribe mechanism

(Gündoğan, 2022). These protocols extend the host-centric, end-to-end paradigm of TCP/IP to IoT, using IP for loose device interconnections. However, by looking at the solutions globally proposed to provide a viable IoT over TCP/IP, the heart of the current IP-based IoT architecture is the application layer with REST instead of the network layer with IP as it is supposed to be. This raises concerns about the approach appropriateness of host-to-host sessions in these disruption-prone environments of (wireless) things, given the data-centric nature at the Internet edge. This has prompted a reconsideration of the current IoT architecture (Gundogan et al., 2021).

One can easily imagine the impact of moving the functionalities provided by the current IP-based IoT stack from the application layer to the network layer. Such a move could enhance efficiency, decrease reliance on the application layer, and significantly streamline application development. The resulting stack would closely resemble the architecture of NDN.

1.2.3 Named Data Networking

NDN shifts the focus of networking from host-centric communication to content-centric data retrieval. Unlike traditional IP networking, where data retrieval depends on host IP addresses, NDN uses URI-like names for routing and forwarding, enabling data retrieval based on content names. Conceptually, it can be compared to an HTTP request-response model operating directly at the network layer instead of the application layer.

Initially derived from Content-Centric Networking (CCN), developed by PARC in 2010, NDN evolved into a standalone architecture under the ICN umbrella. Supported by the Future Internet Architecture Program of the United States National Science Foundation (NSF), NDN is regarded as the most prominent ICN

implementation, addressing key limitations of traditional IP architectures, including IP address management, address translation, exhaustion of address space, and location dependence (Karim et al., 2022).

Figure 1.1 illustrates the architectural shift, with IP packets forming the network's narrow waist in the traditional model, whereas NDN uses named content chunks. This approach minimizes lower-layer dependencies, allowing seamless operation over various link technologies, including legacy IP systems.

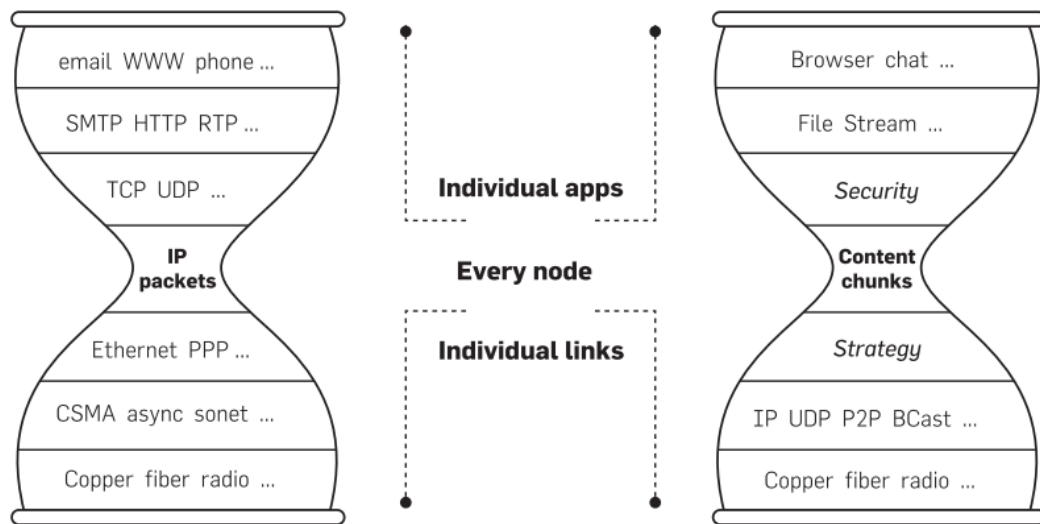


Figure 1.1 Main Building Blocks of IP Architecture (Left) and NDN Architecture (Tariq et al., 2020a)

NDN's core features—caching, naming, packet-level security, and a stateful forwarding plane—make it highly suitable for WSNs, or wireless ad hoc like environments. These environments face challenges such as packet collisions and topology changes due to node mobility, requiring adaptive forwarding strategies to handle the dynamic and unreliable nature of these environments.

In IP-based ad hoc architectures, content retrieval primarily relies on routing strategies, which are considered the intelligent aspect. In contrast, the forwarding action plays a less significant role, as its sole purpose is to execute the routing

decision by transmitting packets hop by hop until reaching the intended destination (Djama et al., 2022b). In that regard, Researchers have extensively explored IP-based routing solutions addressing inherent constraints such as resource limitations (energy and processing) and the dynamic, unpredictable node locations (Khan et al., 2021; Rezaeifar et al., 2019).

NDN incorporates a stateful forwarding plane alongside its routing mechanism. In this approach, nodes keep track of incoming Interests and respond later (negatively or positively) based on data availability. This adaptive and intelligent forwarding action distinguishes NDN from IP-based forwarding. Additionally, NDN's salient features—such as direct implementation of naming and caching at the network layer—enable native support for multicast and anycast forwarding. As a result, NDN provides robust handling of dynamic network topology changes in wireless resource-constrained IoT scenarios.

1.2.4 Location-Based Data Retrieval

Location-dependent data retrieval is an essential requirement in IoT applications such as smart agriculture, healthcare, indoor navigation, and asset tracking. These applications depend on accurately identifying and retrieving data associated with specific geographic locations. While GPS is effective for outdoor localization, its inefficiencies in indoor environments—such as signal degradation and energy consumption—make it unsuitable for resource-constrained IoT devices (Khan et al., 2021; Taki et al., 2020).

NDN offers promising capabilities for location-dependent forwarding in IoT. Unlike traditional IP-based approaches that depend on physical addresses, NDN allows packets to be forwarded based on location-encoded names. For instance, a

name like `/building/floor2/room3/sensor` can serve as a destination identifier, eliminating the need for explicit network addresses. This approach aligns well with the data-centric principles of NDN, where content is decoupled from host addresses. However, effective implementation requires an accurate estimation of the producer's location. While this is feasible in outdoor scenarios using GPS, indoor environments typically rely on centralized servers, offline estimation databases, or manual/static configurations to determine node locations. These methods, while functional, introduce additional communication overhead, extra round-trip delay, and energy consumption, particularly in resource-constrained WSNs. Such of these scenarios can be found in (Chowdhury et al., 2020; Kurihara et al., 2019; Taki et al., 2020).

NDN's native group multicast capabilities, while effective for general data-centric applications, struggle to deliver packets to multiple IoT devices in a specific location. This limitation makes NDN less suitable for multi-source retrieval scenarios, such as retrieving data from several devices in a designated area. Existing solutions attempting to address these challenges must overcome issues like handling local minima—situations where geographically close nodes lack physical connectivity to the destination—and establishing short-lived, highly adaptive routes (Chowdhury et al., 2020). Other solutions use a pattern (or wildcard) like query but are almost exclusive to outdoor location-based scenarios as they require GPS attachment (Hou et al., 2021).

Furthermore, resource-constrained devices typically have only one external communication channel and lack MAC-to-MAC face mapping in NDN's native implementation (Wu et al., 2021). Consequently, solutions often rely on broadcast storms for topology acquisition or when forwarding location routing information is unavailable. Researchers are actively developing forwarding strategies to address this

challenge, although these efforts are still in their early stages. Notably, NDN's forwarding actions are more intelligent than those in IP, while NDN's routing primarily relies on its stateful forwarding plane. Therefore, NDN's forwarding strategy usually involves reactive routing (i.e., topology acquisition), specifically in resource-constrained WSNs (Askar et al., 2023).

1.3 Problem Statement

The shift from the traditional IP model to the NDN communication model within IoT systems has been motivated by the need to overcome challenges inherent in the IP model, including its limitations in providing location attribution. This motivation extends to address IoT systems with wireless resource-constrained environments. The host-oriented model offers a hierarchical and structured IP addressing primarily resolute at the city or country level to support routing and is designed to identify network endpoints rather than specific physical locations. Adding a location attribute to the IP-based host-oriented model poses complexities in managing and administering addresses, let alone the needed update to the networking infrastructure, protocols, and devices to support location-aware routing and addressing, especially in mobile and dynamic wireless resource-constrained environments (Kurihara et al., 2019). In contrast, NDN allows for more flexible and granular location tagging at the content level without tying content to specific IP addresses (host) and offers intrinsic advantages in data distribution and retrieval by decoupling trust from hosts without extensive changes to existing infrastructure. However, it lacks explicit support for device identification and location-based data delivery, which are essential in location-sensitive IoT environments (Hou et al., 2021; Zafar et al., 2021).

Existing solutions attempt to address this gap using NDN's geographic forwarding to reach mobile nodes, or/and naming schemes to represent device locations, but they must handle local minima when nodes geographically close to the destination do not have physical connectivity to it. In addition, they must resort to broadcast storms when location information is unavailable, causing node resource exhaustion. The root problems for these solutions are two-fold: (1) they cannot handle Interest flooding effectively due to the lack of forwarding information, so they have to rely on broadcast and shared wireless channel for multi-hop communication, which does not have broadcast domain limit, and (2) they cannot easily detect or react to forwarding issues (e.g. collision) due to a lack of feedback loop in the data plane at the network layer (Chowdhury et al., 2020; Karim et al., 2022; Prates et al., 2019). As a result, these solutions frequently lead to increased overhead or latency, reduced retrieval and delivery efficiency, and/or compromise NDN's core data-centric principles (Djama et al., 2022a).

Moreover, solutions that integrate location attributes or adopt a non-IP-based host-oriented architecture render native multicast less effective, as the group multicast in such cases targets multiple data from different hosts (or locations) with different names rather than a single data in different places using a shared data name (Azgin et al., 2018; Wu et al., 2021). These solutions map hosts with MAC addresses or geo-coordinates for next-hop forwarding or reaching the final destination, requiring significant memory space, which is unsuitable for resource-constrained IoT networks and contrary to NDN principles centered on data rather than location. Additionally, incorporating a geo-location module (e.g., GPS) for determining these coordinates energy consumption and great memory space to be stored in the node (Djama et al., 2022b), that are not suited for resource-constrained devices.

The shared channel in resource-constrained wireless networks makes it difficult to successfully retrieve data over multiple hops, which means an effective routing/forwarding solution has to make use of short-lived routes and be highly adaptive. Unfortunately, many resource-constrained routing solutions use control messages to acquire topological information and use broadcast to forward packets to next hops. The topology acquisition process is both costly and ineffective in a highly dynamic network. Moreover, unicast to specific neighbors requires MAC-to-MAC face mapping and is not feasible when connectivity changes frequently in uncontrolled physical spaces (Askar et al., 2023).

1.4 Research Objectives

The research aims to introduce a non-IP-based architecture that offers a data-retrieval forwarding strategy tailored for the wireless infrastructure within a resource-constrained internet-of-things network. It should comprehend both data-oriented and location-dependent host-oriented data retrieval, ensuring delivery efficiency concerning retrieval ratio, overhead, and latency. The research pursues the following goals:

- I. Propose a forwarding algorithm based on a naming scheme to support both data-oriented and location-dependent host-oriented data retrieval.
- II. Optimize multiple location reachability for location-based data delivery, in terms of group retrieval latency and delivery ratio.
- III. Propose an entity that optimizes location-dependent data retrieval using relative node-location information and device capability to mitigate congestion in wireless resource-constrained environments.

1.5 Research Scope

The research focuses on implementing a location-dependent data retrieval strategy for NDN-based IoT within resource-constrained wireless environments. The scope of the study is limited to the following:

- I. **Protocol Choice:** The thesis is limited to NDN-based IoT implementations, excluding IP-based IoT solutions. This ensures a focus on content-centric architectures and their applicability to constrained IoT environments.
- II. **Communication Technology:** Algorithms and strategies are developed and tested using IEEE 802.15.4, chosen for its widespread adoption in low-power IoT networks due to its energy efficiency and compatibility with constrained devices (Cena et al., 2020).
- III. **Device Constraints:** The IoT devices in this thesis are characterized by limited processing power, memory, energy, and bandwidth, reflecting real-world resource-constrained IoT environments.
- IV. **Operating System:** All devices in the testbed run on the RIOT operating system, selected for its lightweight, modular design, compatibility with IoT-specific protocols, including NDN, and for the built-in adaptation layer, and available driver for devices TI CC2538, used in the thesis experiment.
- V. **NDN Implementation:** NDN-RIOT is chosen for its lightweight and efficient integration of NDN protocols into RIOT-OS, serves as the framework for this research. It allows the practical evaluation of the proposed algorithms in constrained IoT settings, and its minimum requirement allows it to be installed in the experiment devices, TI CC2538.
- VI. **Evaluation Environment:** The proposed approach is evaluated via testbed experiments conducted within the School of Computer Sciences building at

Universiti Sains Malaysia (USM). The building serves as a controlled environment to simulate real-world IoT deployment scenarios.

- VII. Layered Focus: The research focuses solely on the NDN layers, with no emphasis on link-layer issues, including operating system or hardware-specific constraints or device driver functionalities.

Assumptions:

- I. All devices in the network are assumed to have uniform hardware and software capabilities, including support for the RIOT operating system and NDN-RIOT protocol stack.
- II. The evaluation assumes a stable indoor environment, with minimal external interference from the Wi-Fi signals or unpredictable disruptions that could affect the wireless transmission.
- III. Devices are assumed to maintain at least intermittent connectivity with their immediate neighbors to facilitate topology acquisition and forwarding, as required by the proposed approach. Routing areas are assumed to have one router node, which maintains at least one intermittent connectivity with a gateway. Routing areas must intersect each other to maintain the established topology.
- IV. Devices are assumed to start with sufficient initial energy levels to complete all experimental tasks without the need for recharging.
- V. It is assumed that a hierarchical and structured naming scheme is dynamically established and maintained throughout the experiment, however, device identification and data naming or assumed to be pre-established.

1.6 Expected Contribution

This research aims to contribute to the field of NDN for wireless resource-constrained IoT networks by addressing the research objectives outlined in Section

1.4. The expected contributions are as follows:

- I. A novel location-enabled forwarding algorithm and hierarchical naming scheme for forwarding strategy that are designed to seamlessly integrate data-oriented and location-dependent host-oriented retrieval. The hierarchical naming scheme enhances forwarding decisions, improving data delivery efficiency, particularly in location-dependent IoT environments.
- II. Pattern-enabled naming and forwarding algorithms to optimize location-dependent multicast functionality. These contributions reduce network overhead and enhance retrieval efficiency in location-dependent group data delivery scenarios, ensuring resource-efficient communication.
- III. A dynamic path-selection entity that optimizes resource usage, mitigates congestion, and ensures reliable data retrieval. This entity leverages the location-enabled hierarchical naming and node capabilities (e.g., storage, energy) to establish efficient dynamic routes, structure the network into location-aware domains, assign forwarding roles, and improve overall network performance.

The outcomes of this research are expected to enhance NDN's applicability by demonstrating improved efficiency, reliability, and adaptability in different resource-constrained IoT environments, specifically those with location-dependent requirements.

1.7 Research Methodology

The research methodology is structured into three key phases, as illustrated in Figure 1.2, to systematically address the objectives of this research.

Phase 1: Problem Identification and Analysis:

This phase focuses on identifying limitations in existing NDN-based solutions and analyzing the requirements of resource-constrained IoT environments. A comprehensive literature review is conducted to examine wireless sensor networks, IoT systems, named data networking, and location-dependent solutions. The insights gained are used to clearly define the research problem and establish the foundational understanding necessary for developing a solution.

Phase 2: Development and Design of the Proposed Approach

In this phase, the proposed approach is designed by determining the necessary components, algorithms, and architecture. The following steps guide this process:

- **Component Development:** Design and integrate critical components aligned with the research objectives, focusing on hierarchical naming, adaptive forwarding, and optimize routing mechanisms.
- **Network Hierarchy Design:** Develop a network structure optimized to mitigate congestion and overhead, leveraging node location to suit resource-constrained wireless IoT environments.
- **Naming Scheme Design:** Define a naming scheme that integrates content identity, device identity, and location, enabling data-oriented and location-dependent data retrieval.

- **Path Construction and Routing:** Develop a dynamic routing entity to establish efficient data retrieval paths, ensuring support for both data-centric and host-oriented location delivery.
- **Forwarding Strategy Development:** Create an adaptive forwarding strategy capable of simultaneously addressing proximity-based and location-driven data retrieval. The strategy leverages hierarchical naming and dynamic routing to efficiently handle diverse Interest requests, optimizing both unicast and group retrieval scenarios while minimizing resource use.
- **Environment Setup:** Prepare a suitable NDN-based test environment for IoT networks, including operating systems and necessary techniques, emulating real-world scenarios.
- **Implementation:** Implement the proposed algorithms and strategies into the network environment for comprehensive evaluation.

Phase 3: Evaluation and Validation

This phase evaluates the developed solution by comparing its performance against existing NDN implementations (NDN-RIOT) as well as state-of-the-art solution. Metrics such as data retrieval latency, overhead, and delivery ratios are assessed in a real-world testbed environment. The evaluation validates the proposed approach's ability to address the dual requirements of data-oriented and location-dependent delivery (both unicast and multicast), ensuring reliability and adaptability in resource-constrained IoT systems.

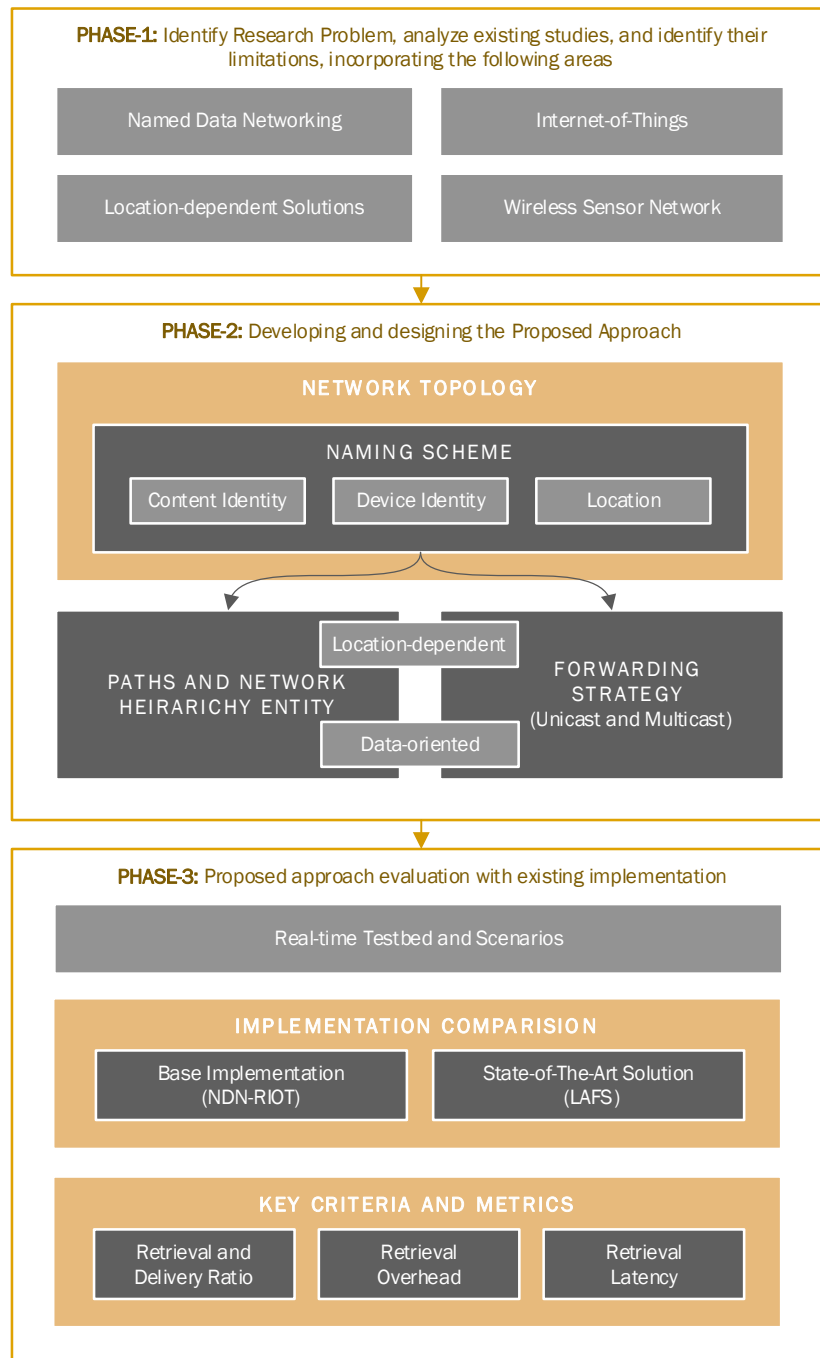


Figure 1.2 The Flow of Research Methodology

1.8 Thesis Outline

The remainder of this thesis is organized as follows:

- Chapter 2 – Literature Review: This chapter presents an in-depth review of the foundational concepts of NDN and its relevance to IoT environments. It evaluates existing solutions for data-oriented and location-dependent delivery

and identifies the challenges and limitations in resource-constrained IoT systems. These insights establish the context for the proposed approach.

- Chapter 3 – Proposed Architecture: This chapter introduces the E-NDN architecture, detailing its components and the rationale behind their design. It describes the Wildcard-based and location-enabled hierarchical Naming Scheme, Dual-Mechanic Forwarding strategy, and the Path-Selection Module. The chapter also outlines how these components work cohesively to address the challenges identified in Chapter 2.
- Chapter 4 – Implementation and Experimental Setup: This chapter discusses the implementation details of the proposed E-NDN architecture, including the algorithms, environment setup, and hardware used in the real-world testbed. It explains the configuration of the network environment and the tools employed for validating the proposed approach.
- Chapter 5 – Results and Analysis: This chapter presents a comparative performance evaluation of E-NDN against existing NDN-based solutions, including LAFS and NDN-RIOT. Metrics such as retrieval overhead, latency, delivery ratios, and resource efficiency are analyzed to demonstrate the advantages of E-NDN in resource-constrained IoT scenarios.
- Chapter 6 – Conclusion and Future Work: This chapter concludes the thesis by summarizing the key contributions and findings. It reflects on the research objectives and highlights how E-NDN addresses the dual requirements of data-oriented and location-dependent delivery. The chapter also outlines potential directions for future research, including further optimization of multicast forwarding and support for node mobility.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter lays the foundation for the research, offering a thorough review of the key concepts, methodologies, and related work that informs the challenges and opportunities in developing NDN architectures, specifically focusing on location-based forwarding strategies and their naming schemes for IoT systems. As IoT networks evolve, the demand for efficient, scalable, and adaptive data retrieval mechanisms becomes increasingly critical, particularly in resource-constrained environments. NDN's data-centric communication model provides opportunities for enhancing data delivery, inherently aligning with the needs of IoT systems. However, adapting NDN for IoT applications requires addressing inherent challenges, such as handling location-dependent data delivery, mitigating broadcast storms, and ensuring efficient multicast support.

This chapter examines these challenges and explores existing forwarding and routing strategies to identify gaps, laying the groundwork for the proposed approach.

- Section 2.2 introduces NDN as a data-centric networking paradigm and discusses its architectural components, naming conventions, packet forwarding mechanisms, and caching strategies. The section emphasizes how these features make NDN a suitable alternative to IP-based systems for IoT environments while addressing challenges such as scalability, resource constraints, and efficient data delivery.
- Section 2.3 delves into the role of NDN in IoT, highlighting its advantages over traditional IP-based protocols. It outlines how NDN's inherent caching, multicast

capabilities, and name-based routing align with the demands of IoT systems, particularly in dynamic and resource-constrained networks. Subsections discuss why NDN is well-suited for location-dependent data retrieval and review its current implementations and software architecture tailored for IoT.

- Section 2.4 categorizes and analyzes location-based forwarding strategies into three primary approaches: Naming-Based Forwarding, Location-Aware Forwarding, and Hybrid Approaches. This section evaluates their naming schemes, multicast capabilities, and forwarding mechanisms, discussing their limitations and alignment with the objectives of this thesis. Key challenges such as multicast inefficiencies, broadcast storms, and handling dynamic topologies are highlighted.
- Section 2.5 provides a critical analysis and discussion of the reviewed literature, identifying gaps in existing solutions and their implications for this research. The section reflects on the limitations of current strategies in addressing dual-orientation data retrieval, multicast capabilities, and resource constraints. These insights guide the development of a novel forwarding strategy that optimizes location-aware data retrieval while addressing the unique challenges of resource-constrained IoT systems.

Finally, the chapter concludes with a summary that consolidates key insights, preparing the groundwork for the proposed approach in subsequent chapters.

2.2 Named Data Networking

NDN redefines traditional networking paradigms by shifting focus from host-centric communication to content-centric communication. This section examines the architecture, naming conventions, forwarding behavior, caching mechanisms, and the

interplay between forwarding strategies and routing, highlighting their relevance to IoT applications.

2.2.1 Architecture

NDN is a data-oriented networking paradigm derived from the concept of content-centric networking (Jacobson et al., 2009). Unlike IP-based systems, NDN directly names data rather than endpoints, addressing limitations like IP exhaustion and inefficient routing in dynamic environments. Figure 2.1(a) illustrates NDN's architecture, which replaces the IP hourglass model's narrow waist with named data. While NDN operates independently, it can leverage existing IP services like DNS or routing protocols such as BGP and OSPF with minimal modifications (Aroosa et al., 2021; Tehrani et al., 2022).

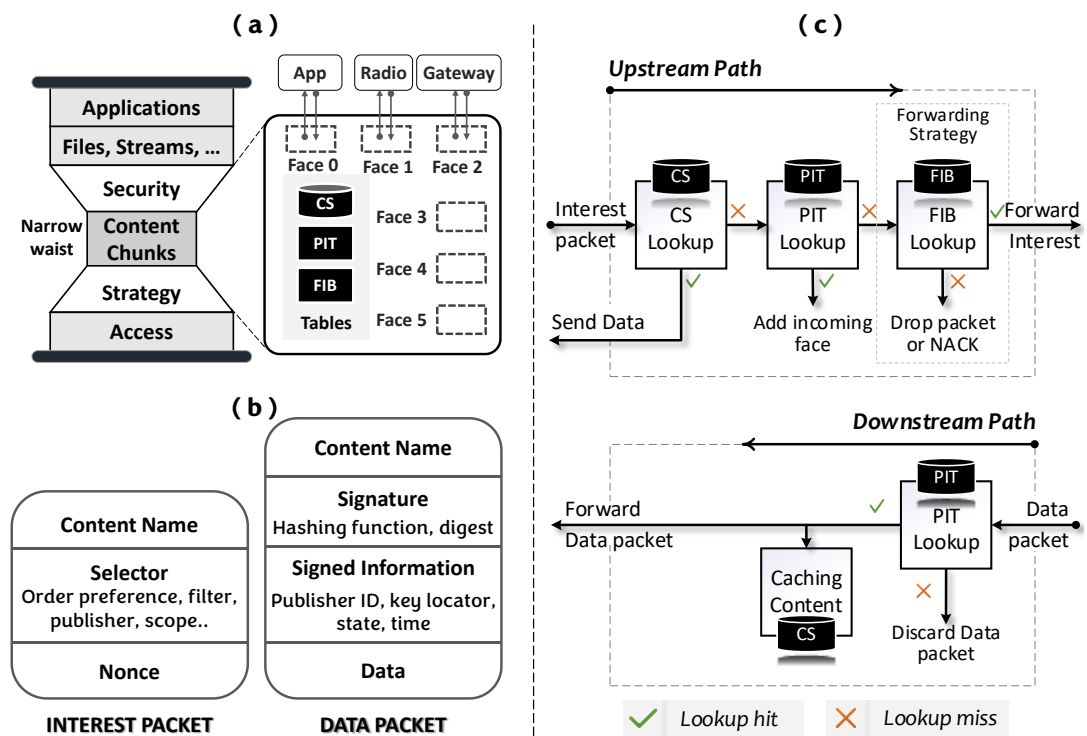


Figure 2.1 (a) NDN Hourglass and Node Architecture, (b) NDN Packets, (c) NDN Forwarding Module (Tariq et al., 2020a)

The architecture features a strategy layer that dynamically selects the optimal links for forwarding based on network conditions and application requirements, optimizing resource use in multihomed devices. A security layer ensures data integrity and authenticity by applying cryptographic mechanisms directly to named data. NDN defines two core packet types (see Figure 2.1(b)): Interest and Data. Interest packets carry data requests, while Data packets deliver responses, embedding cryptographic signatures for verification. Each NDN node maintains three critical data structures:

- Forwarding Information Base (FIB): Guides Interest packets towards potential data sources.
- Pending Interest Table (PIT): Tracks unsatisfied Interests and their associated incoming and outgoing interfaces.
- Content Store (CS): Caches Data packets temporarily for efficient reuse.

This design enables inherent support for multicast and adaptive forwarding, making NDN suitable for resource-constrained IoT environments.

2.2.2 Naming

NDN employs hierarchical, application-specific, and opaque names to identify content, offering flexibility in data retrieval. Names are structured as sequences of components, similar to file paths, enabling efficient lookup and organization. For instance, */usm.my/en/main.html* can denote a webpage, while */sensor/room1/temp* might represent a temperature reading.

Names are matched using the Longest Prefix Match (LPM) algorithm, allowing flexible data segmentation and retrieval. For example, a consumer requesting */usm.my/en/main.html* can receive different versions or segments of

the content if available(NDN Project Team, 2021). The request can be considered a match to the first segment of the third version of the USM home page (information object) having the name */usm.my/en/main.html/3/1*. The consumer could alternatively ask for the different version by requesting the name */usm.my/en/main.html/2*. The component */en* in the example can define the scope of the data and used on the matching and retrieval process. However, while hierarchical names simplify routing, they require careful design to ensure scalability in IoT applications, where dynamic and localized naming schemes are often needed.

2.2.3 Interest and Data Forwarding

Forwarding strategies in NDN enable efficient data retrieval by dynamically routing Interest packets and delivering corresponding Data packets. Upon receiving an Interest (see Figure 2.1c), an NDN node checks its CS for matching content. If unavailable, it consults the PIT to aggregate Interests with identical names and avoid redundant forwarding. Otherwise, it forwards the Interest based on the FIB's longest prefix match. The forwarding strategy governs decisions, (Azamuddin et al., 2023), like where to send Interests or how to handle Data packets. For instance:

- Interest forwarding: Multicast forwarding through interfaces in matched FIB entries.
- Data packet handling: Multicast delivery to interfaces listed in PIT entries, achieving efficient data dissemination.

Adaptive strategies can dynamically adjust forwarding paths based on network conditions, enabling load balancing and reducing congestion. This capability is particularly beneficial in lossy and resource-constrained IoT environments, where network conditions fluctuate frequently.